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CHIRP EXCITATION OF ULTRASONIC GUIDED WAVES (PREPRINT)

Jennifer E. Michaels and Sang Jun Lee

Georgia Tech Research Group

Anthony J. Croxford and Paul D. Wilcox
Department of Mechanical Engineering, University of Bristol

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Jennifer E. Michaels and Sang Jun Lee (Georgia Tech Research Group)
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Georgia Tech Research Group
305 10th Street NW
Atlanta, GA 30332

Department of Mechanical Engineering
University of Bristol
Queen's Building, University Walk
Clifton, Bristol
BS8 1TR

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14. ABSTRACT
Most ultrasonic guided wave methods require tone burst excitations to achieve some degree of mode purity. In addition, it is often desirable to acquire data using multiple frequencies, particularly during method development when the best frequency for a specific application is not known. However, this process is inconvenient and time-consuming, particularly if extensive signal averaging at each excitation frequency is required to achieve a satisfactory signal-to-noise ratio. Both acquisition time and data storage requirements may be prohibitive if responses from many narrowband tone burst excitations are measured. Here chirp excitations are utilized to address the need to both test at multiple frequencies and achieve a high signal-to-noise ratio. A broadband chirp is used to acquire data at a wide range of frequencies, and deconvolution is applied to extract multiple narrowband responses. If only a single narrowband response is needed, a long-time narrowband chirp is used as an excitation, and the short-time tone burst response is similarly extracted during post-processing.

15. SUBJECT TERMS
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Chirp Excitation of Ultrasonic Guided Waves

Jennifer E. Michaels[1], Sang Jun Lee[1], Anthony J. Croxford[2] and Paul D. Wilcox[2]

[1]School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA 30332-0250

[2]Department of Mechanical Engineering, University of Bristol, Bristol, UK

ABSTRACT. Most ultrasonic guided wave methods require tone burst excitations to achieve some degree of mode purity. In addition, it is often desirable to acquire data using multiple frequencies, particularly during method development when the best frequency for a specific application is not known. However, this process is inconvenient and time-consuming, particularly if extensive signal averaging at each excitation frequency is required to achieve a satisfactory signal-to-noise ratio. Both acquisition time and data storage requirements may be prohibitive if responses from many narrowband tone burst excitations are measured. Here chirp excitations are utilized to address the need to both test at multiple frequencies and achieve a high signal-to-noise ratio. A broadband chirp is used to acquire data at a wide range of frequencies, and deconvolution is applied to extract multiple narrowband responses. If only a single narrowband response is needed, a long-time narrowband chirp is used as an excitation, and the short-time tone burst response is similarly extracted during post-processing. Results are shown that demonstrate the efficacy of both broadband and narrowband chirp excitations.

Keywords: Ultrasonics, Structural Health Monitoring, Signal-to-Noise Ratio

1. INTRODUCTION

Guided wave-based methods for ultrasonic nondestructive evaluation (NDE) and structural health monitoring (SHM) are the primary techniques for long range damage detection and characterization in plate-like structures. Because of the highly dispersive and multi-modal of nature guided waves, it is customary to use narrowband excitations so that dispersive effects and number of modes are minimized [1-3]. Typically both the transducer dimensions and the excitation frequency are adjusted to maximize mode purity, which can further improve interpretability of guided wave signals [4]. Often this mode tuning is done empirically by exciting the transducer with a variety of tone burst signals of different center frequencies and widths, and then selecting the one that generates the response exhibiting the best mode purity with the shortest duration time domain pulses.

Guided wave measurements are frequently performed using low voltage excitations, particularly as compared to typical bulk wave excitations in the hundreds of volts, and extensive signal averaging is often employed to achieve a high signal-to-noise ratio (SNR). For ultrasonic bulk wave testing, an alternative technique to improve SNR is to use coded excitations followed by pulse compression [5,6]. For such an approach the transmitter is excited with a broadband but long time signal such as a chirp, white noise signal, or a pseudo-random sequence. The energy of the excitation is significantly increased, and post-processing via either a matched filter or Wiener filter can map duplicates of the excitation pulses to short time impulse-like echoes [7]. Either filtering approach can be effective for many ultrasonic applications where a high SNR broadband response is difficult to achieve, such as testing of concrete [8], air-coupled ultrasonic

methods [9], ultrasonic imaging of wood [10], and characterization of scatterers [11]. In contrast, for the problem considered here, a narrowband response is specifically desired to facilitate signal interpretation by minimizing dispersive effects and maximizing mode purity. The analysis approach taken is simple frequency domain deconvolution to map the measured response to the desired response. The work shown here is an extension of that reported by the authors in [12] and [13].

The main contribution of this paper is neither the signal processing, which is quite simple, nor the idea of a chirp excitation, which is well-known, but the efficient implementation of guided wave data acquisition. The authors, from two laboratories in different continents, were both motivated by the practical concerns of efficiently acquiring high quality guided wave data, and have experienced the enormous impact of using chirp excitations followed by rapid post-processing. This paper is an attempt to convince all guided wave experimenters of not only the significant advantages of such an approach, but that it is also an enabling technology for practical field implementation.

2. THEORY

The term "chirp" refers to a sinusoidal signal for which the frequency is a function of time; the amplitude may also vary. For a typical chirp, the frequency is linearly swept from a minimum value to a maximum value over a fixed time interval while the amplitude is held constant. The equation for such an excitation is,

$$s_c(t) = w(t)\sin\left(2\pi f_0 t + \frac{\pi B t^2}{T}\right), \tag{1}$$

where f_0 is the starting frequency, T is the duration of the chirp, and B is the chirp bandwidth. The function $w(t)$ is a unit amplitude rectangular window starting at $t = 0$ and having a duration of T. The Fourier transform of $s_c(t)$ is $S_c(\omega)$, where ω is the angular frequency.

Consider a guided wave transmitter excited by a known chirp function and the associated receiver, and let $h(t)$ be the corresponding impulse response and $H(\omega)$ its Fourier transform, also known as the transfer function. Included in $H(\omega)$ are the transfer functions of the transmitter and receiver, all instrumentation effects, and the Green's function(s) needed to describe wave propagation between transmitter and receiver. The entire system, which consists of the instrumentation, transducers and structure, is well-modeled as a linear system, and the response to the chirp excitation can thus be expressed in the frequency domain as,

$$R_c(\omega) = H(\omega)S_c(\omega)\,. \tag{2}$$

Let $s_d(t)$ be the desired excitation, which here is a tone burst. In the frequency domain,

$$R_d(\omega) = H(\omega)S_d(\omega)\,. \tag{3}$$

Since the chirp response is known via measurement and both excitations are known, the response to $s_d(t)$ can be obtained as,

$$R_d(\omega) = R_c(\omega)\frac{S_d(\omega)}{S_c(\omega)} = R_c(\omega)G(\omega)\,. \tag{4}$$

It can be seen that $G(\omega)$ is a filter constructed from the Fourier transforms of the chirp and tone burst excitations. If the bandwidth of the desired excitation falls within that of the chirp, then division in the frequency domain is not problematic and $G(\omega)$ can be readily computed. Although a linear chirp with constant amplitude is given as an example in Eq. (1), any chirp signal can be effectively used as long as the bandwidth is sufficient to enable the filter $G(\omega)$ to

be constructed. An additional advantage of this filtering is direct removal of incoherent noise outside the bandwidth of interest.

3. BROADBAND CHIRP RESULTS

As an example of a broadband chirp excitation, consider the chirp signal shown in Figure 1(a) where the frequency sweeps from 50 kHz to 500 kHz over a 200 μs window. Suppose the desired excitation is the tone burst signal of Figure 1(b), which is a Hanning-windowed sinusoid centered at 400 kHz and with a duration of 5 cycles. The measured response to the chirp for two PZT disc transducers mounted 191 mm apart on a 3.175 mm thick aluminum plate is shown in Figure 2(a). Although this chirp response cannot be interpreted in the time domain, the response to the tone burst can be computed as per Eq. (4). Figure 2(b) compares this computed response to the separately measured tone burst response where the amplitudes are scaled so that both signals have unit energy. The two signals are essentially identical down to even the smallest details except that the one computed from the chirp response has slightly less noise than the directly measured tone burst response, which is only evident on the zoomed signal.

The waterfall plot of Figure 3 shows a suite of tone burst responses computed from a single chirp response by varying the center frequency from 100 kHz to 400 kHz in 25 kHz increments. Each tone burst is a five cycle Hanning-windowed sinusoid, and the transducers were located 286 mm apart on a 3.175 mm thick aluminum plate. Although the plate thickness is the same as that of Figure 2, these signals were obtained from a plate larger in extent so that direct A_0 and S_0 arrivals could be unambiguously identified. All waveforms of Figure 3 were normalized to unity amplitude prior to plotting to emphasize the relative modal content of each signal. It can be seen

that the response at 100 kHz is almost pure A_0, whereas the greatest purity of the faster S_0 mode is at 400 kHz. It is thus expected that these two frequencies would be most useful for typical guided wave NDE and SHM applications for which mode purity is desired.

The same chirp response can also be used to investigate the effects of changing the number of tone burst cycles for a particular excitation frequency. Since guided waves are dispersive, there is generally a tradeoff between bandwidth and echo duration in the time domain. Unlike bulk waves, a wide bandwidth does not necessarily lead to a short duration time domain pulse. For a given propagation distance, there is usually an optimum number of cycles that leads to the shortest duration echo. For example, Figures 4 and 5 show waterfall plots for 100 kHz and 400 kHz tone burst excitations, respectively, as the number of cycles varies from two to nine. It can be seen in Figure 4 that the 2-cycle 100 kHz excitation results in the shortest duration direct arrival pulse for the A_0 mode, although the broader bandwidth of this pulse degrades mode purity somewhat as can be soon by the slightly larger initial S_0 arrival. The 3-cycle response offers similar pulse duration with a smaller S_0 contribution. In Figure 5, the 7-cycle 400 kHz excitation appears to yield the shortest S_0 direct arrival, although the distinction isn't as clear as for the A_0 signals at 100 kHz. These observations are certainly not all-inclusive, but are typical of the information that can be gleaned from a single chirp response.

Both the number of cycles and the frequency can be varied simultaneously to optimize both. Using the results from Figures 4 and 5, the number of cycles is continuously varied from 3 to 7 as the frequency increases from 100 kHz to 400 kHz. The envelopes of the resulting signals are calculated from their Hilbert transforms and are plotted in the form of an image in Figure 6. The

frequency-dependent wave speeds of both the faster S_0 mode and the slower A_0 mode are clearly visualized.

The implications of using broadband chirp excitations to record multi-frequency data can be considerable. For example, consider a spatially distributed transducer array comprising eight individual elements, which results in a total of 56 possible transducer pairs. For example, if it is desired to record tone burst data from 50 to 525 kHz in increments of 25 kHz for all possible pairs, then a total of 20 separate signals must be recorded for each pair. Using a chirp excitation directly reduces both the time and data storage requirements by this factor of 20 assuming that all data acquisition functions are fully automated. Another significant advantage of the chirp excitation is that the number of cycles can be optimized for each frequency without recording additional data.

4. NARROWBAND CHIRP RESULTS

A narrowband chirp excitation may be effectively used to significantly improve the signal-to-noise ratio (SNR) without time domain averaging. Suppose the support, or length, of the desired tone burst excitation is T_{tb} and the bandwidth is F_{tb}, and that a chirp is defined that distributes the bandwidth of the tone burst over a longer time window of length $N \times T_{\mathrm{tb}}$. If the tone burst response is extracted as per Eq. (4), the SNR should increase by a factor of $\sqrt{N}$, which is the same degree of improvement expected if N time signals are averaged.

(Bristol contribution: Does not need AFRL clearance)

5. DISCUSSION AND CONCLUSIONS

This paper has presented a simple method for extracting narrowband tone burst responses using chirp excitations, and has demonstrated the efficacy of this approach for both broadband and narrowband chirps. The results presented here are representative of what the authors have implemented to date, and are certainly not intended to be exhaustive. For example, nonlinear chirp excitations could be readily implemented to enable simultaneous acquisition of multiple distinct frequency ranges with a very high SNR. Similarly, responses to other narrowband excitations, such as chirplets, could readily be extracted. In addition, the benefits of shorter acquisition times, reduced data storage requirements, and higher SNR resulting from chirp excitations are expected to be even more significant for full wavefield capture using, for example, laser vibrometers or air-coupled transducers because of the unavoidably large amounts of data required [14].

There are two minor downsides to using a chirp excitation. The first is that raw signals cannot be directly interpreted in the time domain, which is not a limitation for an automated system and is only a minor inconvenience in the laboratory. The second is that the time window for acquisition must be longer than the desired time window for analysis by an amount equal to the length of the chirp; this is only an issue during initial configuration of the data acquisition system. It is therefore recommended that chirp excitations be routinely used for guided wave inspection and monitoring applications, as is now done by the authors in laboratories at both the Georgia Institute of Technology and the University of Bristol.

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REFERENCES

1. D. N. Alleyne and P. Cawley, "The interaction of Lamb waves with defects," *IEEE Transactions on Ultrasonics, Ferrolectrics, and Frequency Control*, **39**(3), pp. 381-397, 1992.

2. T. Ghosh, T. Kundu and P. Karpur, "Efficient use of Lamb modes for detecting defects in large plates," *Ultrasonics*, **36**, pp. 791-801, 1998.

3. J. L. Rose, "A baseline and vision of ultrasonic guided wave inspection potential," *Journal of Pressure Vessel Technology*, **124**, pp. 273-282, 2002.

4. V. Giurgiutiu, "Tuned Lamb wave excitation and detection with piezoelectric wafer active sensors for structural health monitoring," *Journal of Intelligent Material Systems and Structures*, **16**, pp. 291-305, 2005.

5. M. Pollakowski and H. Ermert, "Chirp signal matching and signal power optimization in pulse-echo mode ultrasonic nondestructive testing," *IEEE Transactions on Ultrasonics, Ferrolectrics, and Frequency Control*, **41**(5), pp. 655-659, 1994.

6. M. Toshino, R. Okuno, A. Nagemune and K. Nishifuji, "Next generation on-line ultrasonic testing system, using real-time chirp pulse compression processing," *Materials Science Forum*, **210-213**, pp. 791-798, 1996.

7. J. Cowe, J. Gittins and D. H. Evans, "Improving performance of pulse compression in a Doppler ultrasound system using amplitude modulated chirps and Wiener filtering," *Ultrasound in Medicine and Biology*, **34**(2), pp. 326-333, 2008.

8. B. Koehler, G. Hentges and W. Mueller, "Improvement of ultrasonic testing of concrete by combining signal conditioning methods, scanning laser vibrometer and space averaging techniques," *NDT&E International*, **31**(4), pp. 281-287, 1998.

9. T. H. Gan, D. A. Hutchins, D. R. Billson and D. W. Schindel, "The use of broadband acoustic transducers and pulse-compression techniques for air-coupled ultrasonic imaging," *Ultrasonics*, **39**, pp. 181-194, 2001.

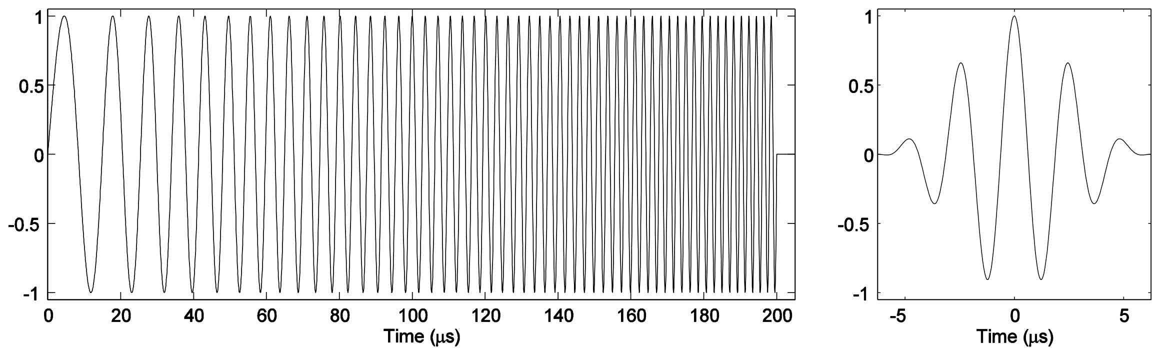
10. T. H. Gan, D. A. Hutchins, R. J. Green, M. K. Andrews and P. D. Harris, “Noncontact, high-resolution ultrasonic imaging of wood samples using coded chirp waveforms,” *IEEE Transactions on Ultrasonics, Ferrolectrics, and Frequency Control*, **52**(2), pp. 280-288, 2005.

11. S. G. Kanzler and M. L. Oelze, “Improved scatterer size estimation using backscatter coefficient measurements with coded excitation and pulse compression,” *Journal of the Acoustic Society of America*, **123**(6), pp. 4599-4607, 2008.

12. J. E. Michaels, S. J. Lee, J. S. Hall and T. E. Michaels, "Multi-mode and multi-frequency guided wave imaging via chirp excitations," *Proceedings of SPIE, Health Monitoring of Structural and Biological Systems*, **7984**, T. Kundu (Ed.), SPIE, pp. 79840I (11 pages), 2011.

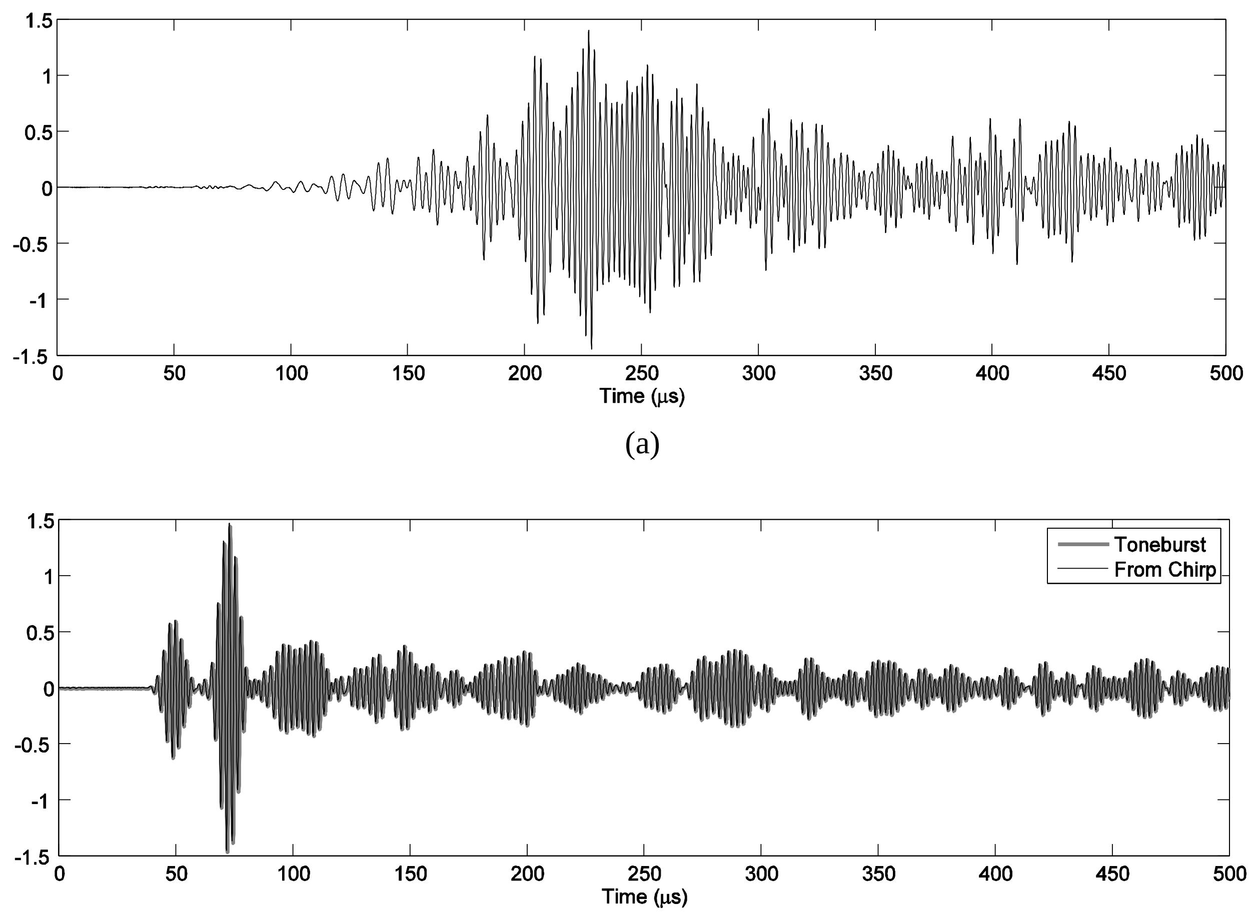
13. A. J. Croxford, O. Putikis and P. D. Wilcox, “Efficient guided wave SHM baseline capture and selection,” *Proceedings of the 8th International Workshop on Structural Health Monitoring*, F.-K. Chang (Ed.), DEStech Publications, Inc., Lancaster, PA, pp. 2067-2074, 2011.

14. T. E. Michaels, J. E. Michaels, S. J. Lee and X. Chen, "Chirp generated acoustic wavefield images," *Proceedings of SPIE*, *Health Monitoring of Structural and Biological Systems*, **7984**, T. Kundu (Ed.), SPIE, pp. 79840J (11 pages), 2011.



(a) (b)

Figure 1. (a) Linear chirp signal from 50 to 500 kHz. (b) Hanning-windowed tone burst excitation centered at 400 kHz and with a duration of 5 cycles.



(a)

(b)

Figure 2. Measured data for two transducers located 191 mm apart. (a) Response to the linear chirp excitation. (b) Comparison of directly measured response to a 400 kHz excitation to that calculated from the measured chirp response.

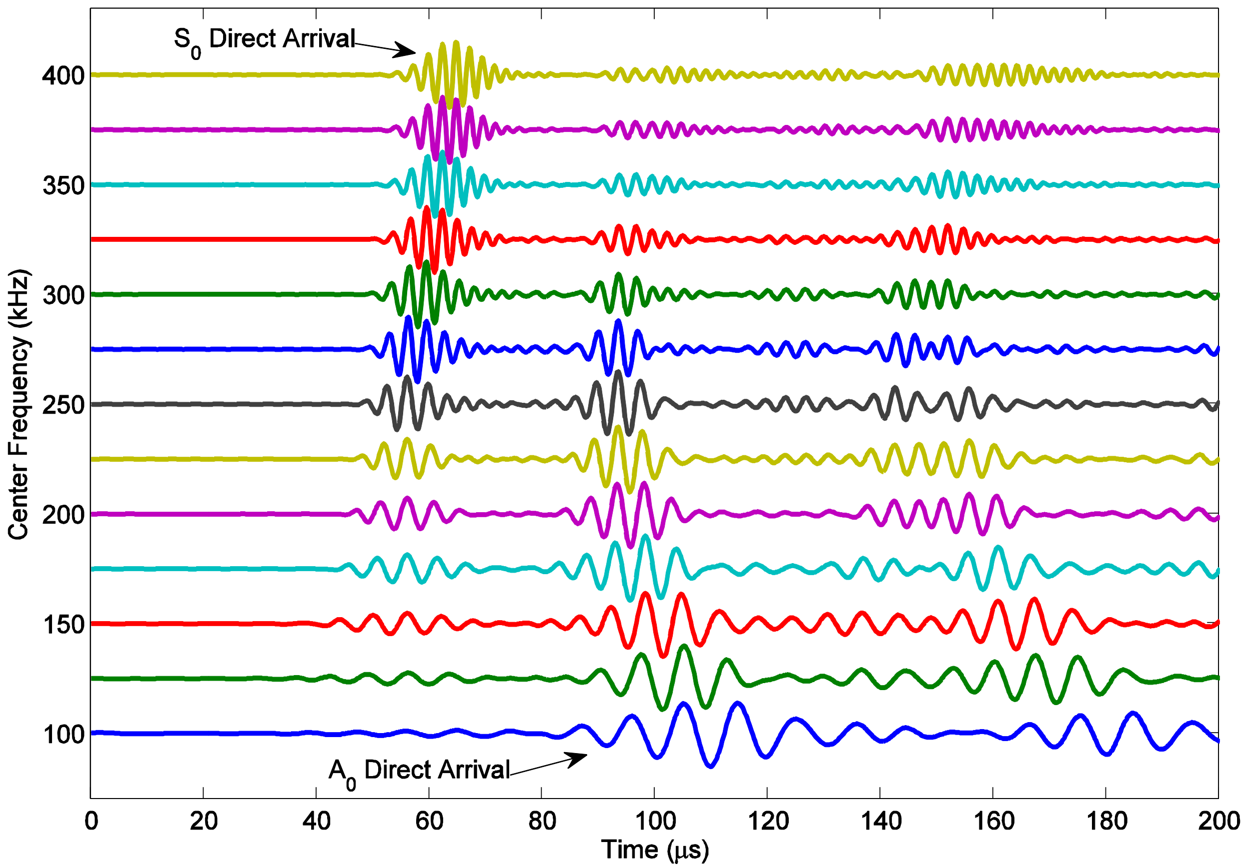


Figure 3. Responses to 5-cycle, Hanning windowed tone bursts at various frequencies as generated from the measured chirp response. The transducers were separated by 286 mm, and they were attached to a 914 × 914 × 3.175 mm aluminum plate.

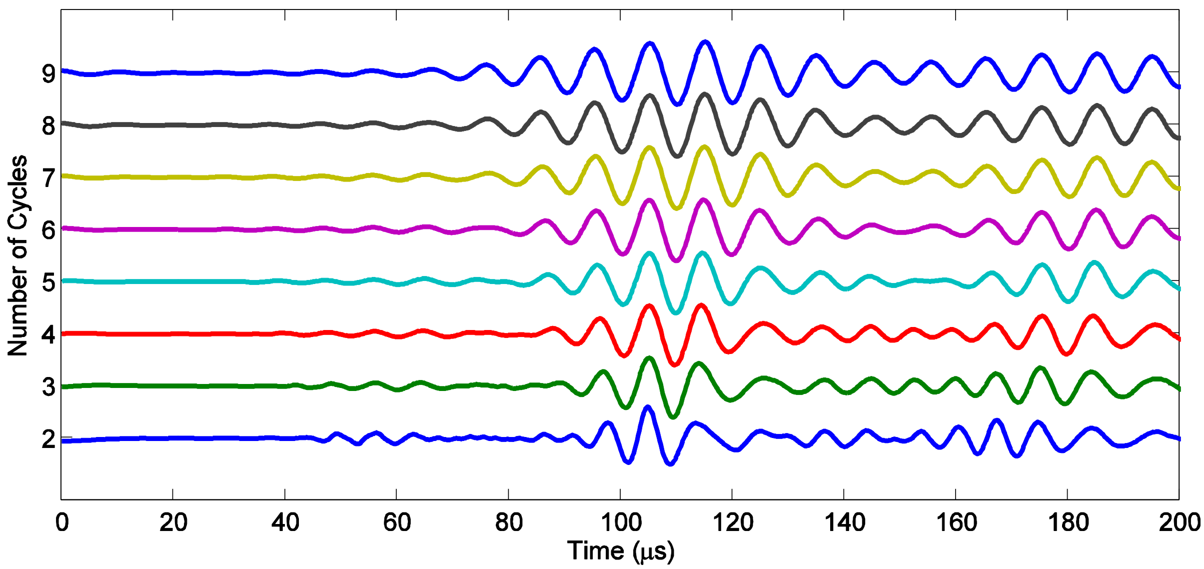


Figure 4. Responses to 100 kHz, Hanning windowed tone bursts at various numbers of cycles as generated from the chirp response. The transducers were separated by 286 mm, and they were attached to a 914 × 914 × 3.175 mm aluminum plate.

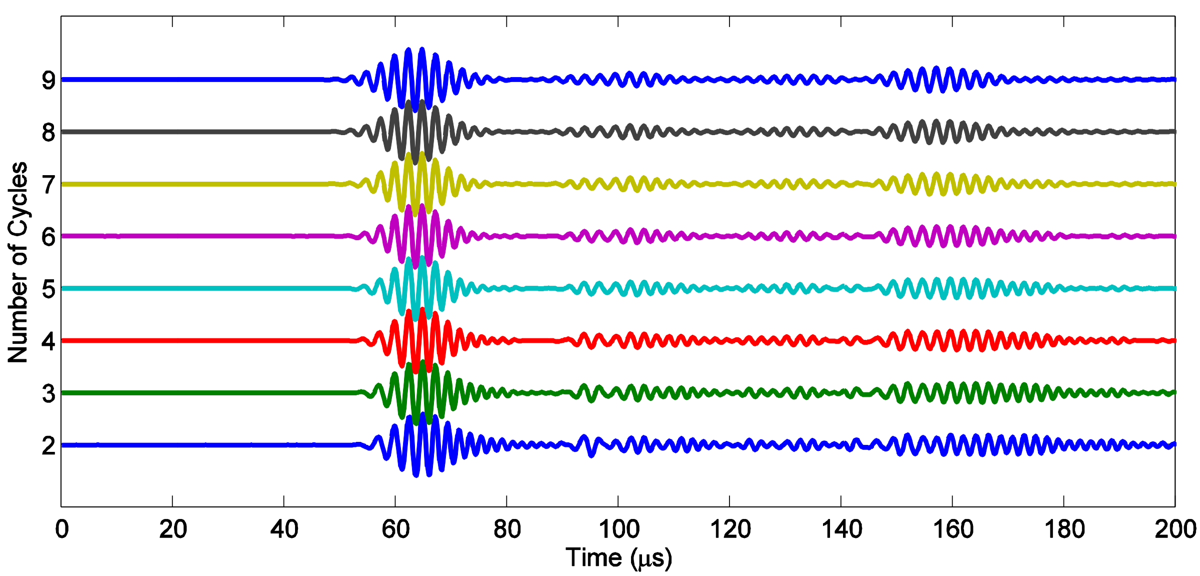


Figure 5. Responses to 400 kHz, Hanning windowed tone bursts at various numbers of cycles as generated from the chirp response. The transducers were separated by 286 mm, and they were attached to a 914 × 914 × 3.175 mm aluminum plate.

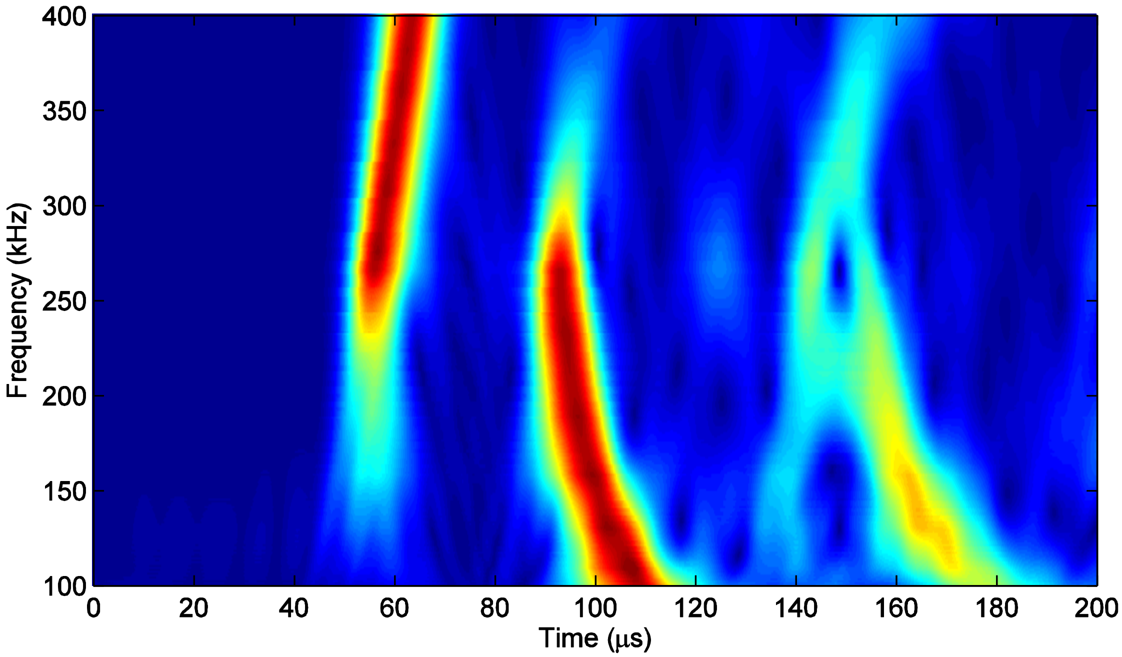


Figure 6. Responses to Hanning windowed tone bursts from 100 kHz to 400 kHz while the number of cycles are continuously varied from 3 to 7.